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SILICONE INSULATION TILT ANGLE IMPACT ON ITS PERFORMANCE UNDER 1000 h OF SALT FOG AGING AND AC VOLTAGE

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Abstract

The investigation focusses on the impact of the inclination angle with respect to the horizontal of hydrophobic elastomer silicone insulation on its performance during aging under salt fog and high AC voltage. The objective of this study is to quantify the leakage current along the surface of silicone insulation as a function of its inclination angle and duration of exposure to salt fog over 1000 hours ageing period. Upon completion of the ageing process, the silicone elastomer samples were characterized through surface roughness measurements, visual inspection of surface morphology, and evaluation of their hydrophobicity.
The results indicated that no burn marks or surface erosion was observed on the insulation after exposure to salt fog. Furthermore, the hydrophobic properties of silicone insulation were effectively retained over time under salt fog conditions, particularly at high inclinations. These findings suggest that increasing the tilt angle contributes to improving insulation performance during 1000 h of salt fog exposure.

Keywords: *Silicone insulation, Salt Fog, Inclination angle, Ageing, AC Voltage.*

I. Introduction

Over recent decades, polymeric insulators have become a preferred choice for outdoor insulation in electrical power distribution and transmission lines due to their excellent performance. Their lightweight nature, ease of handling and installation, along with their strong hydrophobic properties, make them highly advantageous compared to traditional insulating materials [1-3].
Under rain, fog or condensation, water droplets form on the surface of these insulators, due to their excellent hydrophobicity [4,5]. As a result, conductive contamination dissolved in water is discontinuous, leading to the limitation of leakage currents and the reduction of electrical discharges even under severe pollution conditions [6].
Despite their numerous advantages, the performance of polymeric insulators can be compromised under electrical stress due to the presence of water droplets on their surfaces. These droplets disturb the electric field distribution, promoting the initiation of surface discharges. Such discharges progressively degrade hydrophobicity, alter the surface morphology, and accelerate material deterioration. This effect is particularly pronounced when the water contains salt particles, as in salt fog conditions, which intensify erosion and ageing processes in silicone insulation materials [7-9].
The influence of salt spray on silicone insulators has attracted a great deal of attention from scientific researchers and industry experts. Investigations are focused on the study of insulator ageing and surface degradation, caused by circulation of leakage currents on their surfaces under the effect of accelerated aggressive atmospheric conditions such as simulated salt spray in the laboratory [10-13]. However, the effect of any shed’s inclination of such insulators on their ageing under salt spray has not been sufficiently investigated and requires further research. This is one of the obvious reasons why we have analyzed this parameter in this paper.
This study presents a laboratory-based investigation into the impact of varying the inclination angle of hydrophobic silicone insulation surfaces on their performance under alternating current (AC) voltage in

the presence of salt spray. The leakage current was monitored as a function of both the inclination angle with respect to the horizontal and the duration of exposure to the salt fog environment. Additionally, changes in the chemical and physical properties of the insulating surfaces such as erosion, hydrophobicity loss, and surface roughness were systematically analyzed. The findings provide valuable insights into the operational behavior of silicone insulators and offer an experimental foundation for the design and selection of robust, high-performance outdoor insulation systems.

II. Material and methods

II. 1 Sample preparation and experimental set-up

Silicone elastomer samples (POWERSIL XLR 600 A/B) were used in this investigation. For each inclination angle (0°, 30°, 45°, 90°) of the insulation with respect to the horizontal, the analysis was carried out on 4 flat specimens (S_1, S_2, S_3, S_4) of dimensions (10 * 5 * 0.6) cm^3 (Figure. 1). This type of material was chosen for its resistance to ageing, UV rays and chemicals, making it suitable for use in harsh environments conditions. POWERSIL XLR 600 also has excellent hydrophobic properties, and its static contact angle with a 5 µl drop of water measured in the laboratory using a goniometer is equal to 110°.

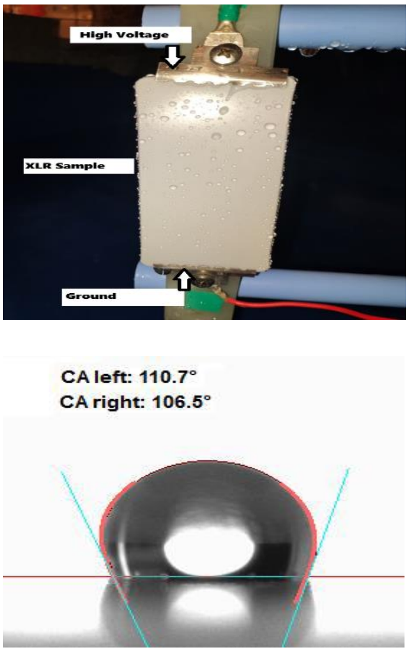


Figure 1. XLR600 sample attached to a device inclined at 90° with respect to the horizontal

Samples are attached to a device that allows the variation of the tilt angle from 0° to 90° (Figure 1). It is made of metal and tinted with several layers of insulating tint to prevent corrosion that could be caused by contact with the saline solution. This device is placed in the middle of the fog chamber. For each tilt angle α (0°, 30°, 45°, 90°), the insulation is exposed to salt spray for a period of up to 1000 h.

II. 2 Salt solution

The electrical conductivity of the sprayed contaminant solution was 1.78 mS/cm. It is obtained by adding a quantity of Magnesium Nitrate (Mg (NO3)2) to a volume of tap water with a concentration of 1Kg/m^3 (1g/L) according to the standard: IEC 62217.

II. 3 Fog chamber and leakage current measurement

The fog chamber is 1.6 m * 1.6 m * 2.5 m in size. Its walls are made of PVC, transparent and allow visual inspection of the samples tested inside. The chamber is equipped with a plexiglass door, allowing access to its interior when not in operation for sample installation or removal, system adjustments, and post-analysis cleaning. Two type D 505 atomizers (Defensor AG, Pfäffikon, CH) are installed in opposite corners of the chamber to ensure a uniform distribution of salt fog. The atomizers are regulated to maintain the precipitation rate specified in Table 2 of IEC 62217, with a spray rate set at 1.5 ± 0.5 ml/h.

Figure 2. Fog chamber

The insulation was subjected to 1 kV AC voltage and exposed to salt spray for a maximal period of 1000 h. The maximum leakage current that can flow and short-circuit the samples surface should not exceed the leakage current threshold set at 2 mA for 2 seconds. Beyond this value, the voltage switches off automatically. These leakage currents are measured during the entire analysis period using NextView®4 software. The results of the leakage current measurements collected are of order of 176,000 values for each hour of testing, over the period of exposure to the salt fog.

II. 4 Hydrophobicity measurement

The hydrophobicity of our samples is determined and measured using the static contact angle method. This method involves measuring the static contact angle of a 5 µl drop of water deposited on the insulation surface before and after exposure to salt spray, using an optical contact angle measurement and contour analysis system OCA35 (Goniometer), in accordance with DIN IEC/TS62073, VDE 0674-276.

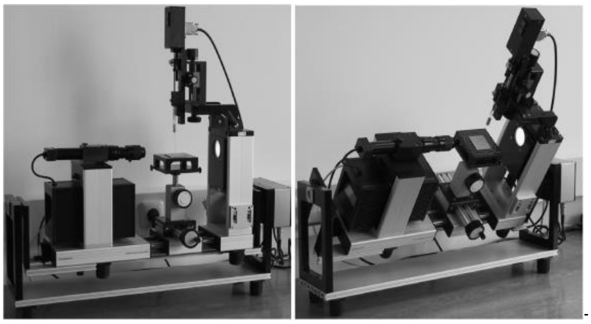


Figure 3. Hydrophobicity measurement with Goniometer

Five measurement points at different locations along the insulating surface are taken for each sample. The value considered at the end is the calculated arithmetic mean of these 5 static contact angle values for each sample.

II. 5 Roughness measurement

Roughness measurement of our samples before and after exposure to salt spray under AC voltage is carried out according to the norm ISO 4287, using a numeric microscope. After cleaning and conditioning the samples at a temperature of (23±2) ° and a humidity of (45 ± 5) %, they are immediately examined under the microscope, and the value of the Average surface roughness (Ra) is directly indicated and given.

Five measurements in different areas of the sample surface were taken to obtain a representative average of surface roughness.

III. Results and discussion

III.1 Visual inspection of samples after ageing

At the end of the ageing process, the samples removed from the fog chamber were subjected to a visual inspection to study the condition of their surfaces after exposure to salt spray for up to 1000 hrs. This inspection revealed no erosion, burns or cracks on any of the insulating surfaces. A slight discoloration of the samples was noted, which is usual for polymer insulators after ageing [14,15], this is caused by several mechanisms such as oxidation, chemical reactions and migration of the pigments responsible for material coloration. This is attributed to the effect of moisture and salts present in the salt fog, which penetrates the material's structure and promotes oxidation and undesirable chemical reactions. These reactions may lead to the breakdown of chemical bonds and alterations in the material's structure. Furthermore, high humidity and reactive salts can interact with the functional groups of the material, forming chemical compounds that may dissolve or modify the pigment particles.

III.2 Morphology and surface roughness

The performance of an insulation is strongly influenced by its surface morphology [16]. Ageing of silicone insulation under salt spray and AC voltage can lead to surface roughness. This can be caused by the formation of microcracks and pores, which can accumulate pollutants and salts from the environment. This leads to the formation of a thin conductive layer and the appearance of electrical discharges on the insulating surface.

Figure 4 shows the evolution of surface roughness samples S_1, S_2, S_3 and S_4 for each inclination angle α (0°, 30°, 45°, 90º), after ageing in a salt spray and AC voltage environment. This shows that all aged samples present a slight increase in surface roughness compared to a virgin sample (S_{virg}), regardless of their inclination. This small increase is due to the low voltage applied to the samples as roughness increases with the rise in applied voltage [17] and as the voltage applied in this study did not exceed 1 kV only a small increase in roughness was observed.

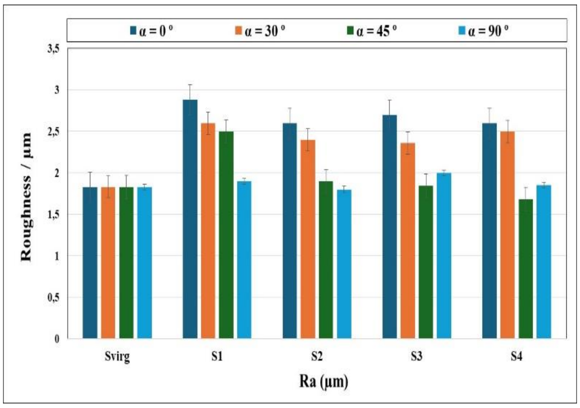
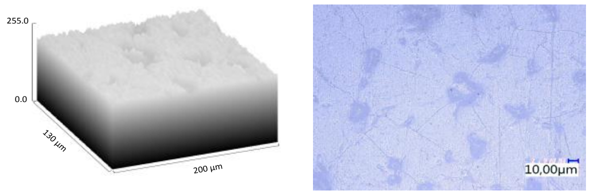


Figure 4. Surface roughness of inclined samples at different inclination angles

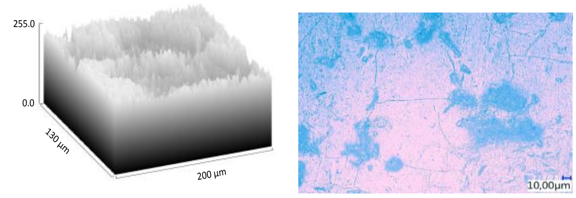
Although surface roughness is not directly related to the inclination angle, the variation in α has a significant impact on surface wettability. A low inclination angle leads to high surface wetting, which increases the frequency of occurrence and circulation of electrical discharges. This leads to the appearance of cracks and an increase in surface roughness and the opposite was observed for a high inclination (Figure 5).

The 2D images presented in Figure 5 were captured using a microscope on the surfaces of the samples after ageing, at various inclination angles α. To better visualize the morphology and appearance of the samples, the ImageJ software was used to generate 3D representations from these 2D images. This method is reliable for qualitative and comparative analysis of surface morphology. It can serve as a useful preliminary or complementary tool for more advanced techniques.

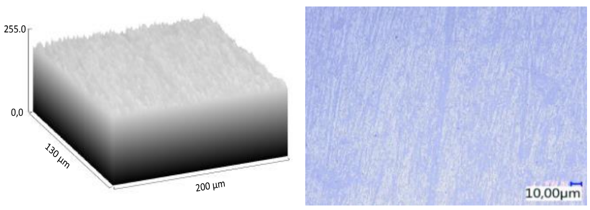
Figure 5 shows that, even when exposed to salt spray for a long period (1000 h), the insulation in the vertical position was able to resist ageing without significantly affecting its roughness. On the other hand, when the insulation is in the horizontal position (α = 0°), its surface becomes rougher due to the formation of salt deposits which can create asperities on these surfaces and accelerate the degradation of the insulation, resulting in their flashover after a short period of exposure to salt spray (maximum 192 h) and thus reducing its electrical performance and operating life.



(a)



(b)



(c)

Figure 5. Surface morphology before and after ageing, represented by a 2D image captured with a microscope (left) and a 3D generated using ImageJ (right), (a): Virgin sample, (b): α = 0˚, (c): α = 90

III.3 Hydrophobicity of aged insulation

Figure 6 shows a comparison of the static contact angle measured on sample surface before and after ageing when it is tilted at 90° and subjected to alternating voltage.

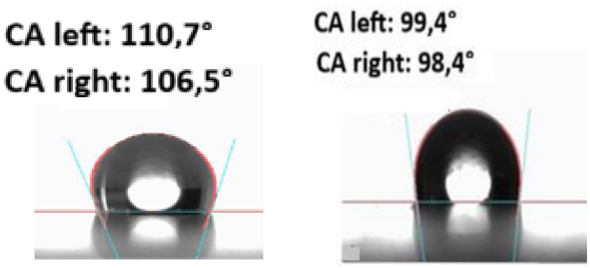


Figure 6. Static contact angle before and after insulation exposure to salt spray, α = 90°

Figures 7, 8, 9 and 10 illustrate the different static contact angles of the sample surfaces before and after exposure to salt fog, corresponding to inclination angles α of 0°, 30°, 45° and 90º, respectively. A decrease in static contact angle was observed on all samples regardless of their inclination relative to the horizontal, as should also be noted that the exposure time (T_{exp}) to the salt fog is limited by the deactivation criterion (threshold current) and it differs from one sample to another.

This drop in contact angle measured after ageing is mainly due to electrical discharges occurring on the insulating surface of the sample in the presence of moisture when subjected to alternating voltage during ageing in a salt fog environment [18]. These electrical discharges release a large amount of energy, which can break the chemical bonds within the polymer molecules. This leads to a reduction in hydrophobic groups and an increase in the precipitation of hydrophilic groups due to salts cementing the surface of the insulator. As a result, the static contact angle decreases [19], which may increase the electrical conductivity of the insulator and consequently reduce its flashover voltage.

It can be seen from figures 8 and 9 that the insulating surfaces inclined at 30° and 45° reached a nearly similar reduction in hydrophobicity, despite being exposed to the salt fog for different durations. The samples inclined at 45° were subjected to a slightly longer exposure period than those at 30°, indicating that the dielectric performance of the insulation at 45° is comparable to that at α = 30°.

According to figure 7, sample S_1 was removed from the salt fog chamber after only a few hours of exposure. This was due to leakage currents exceeding the predetermined threshold, caused by the degradation of the surface hydrophobicity. This degradation continued the other samples and became increasingly significant as the ageing duration increased. The highest dielectric strength was observed in sample S_4, which maintained its electrical insulation properties for an exposure period to the salt fog not exceeding 192 hours. This can be explained by the fact that, in the horizontal position of the insulation, the samples become more humid due to the accumulation and coalescence of water droplets on their surfaces. This promotes the occurrence of many successive and repeated electrical discharges over a short period of time. These discharges, along with leakage currents, accelerate ageing of sample surfaces, leading to a rapid degradation of their hydrophobic properties, failure of samples, and a reduction in their service life.

As shown in Figure 10, the static contact angle measured for S_1, S_2, S_3, et S_4 was in the range of 92 to

98.The highest measured static contact angles compared to others inclined samples with α = 0º, 30º and 45º.This indicates that, despite the hydrophobicity reduction after 1000 hours of ageing, the samples in vertical position still retained their hydrophobic properties.

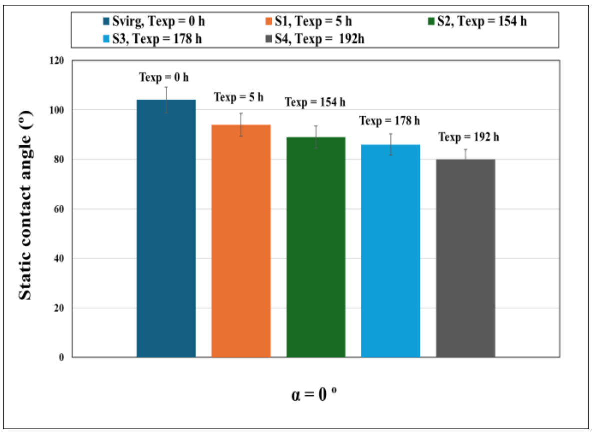


Figure 7. Static contact angle after exposure of insulation to salt fog, α = 0°

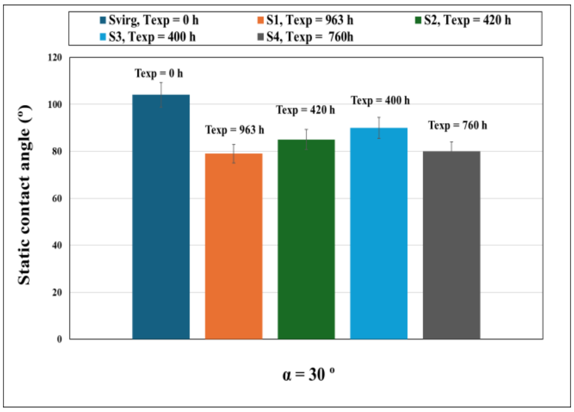


Figure 8. Static contact angle after exposure of insulation to salt fog, α = 30°

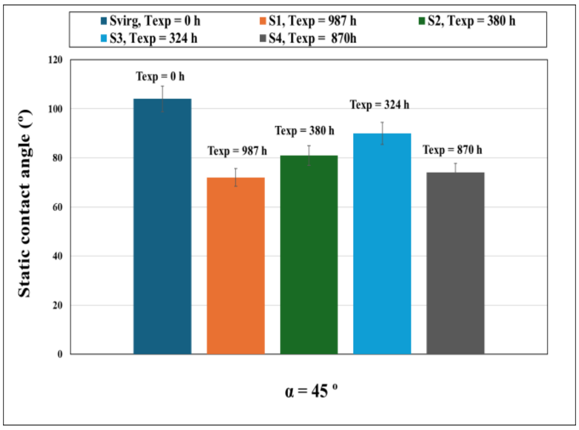


Figure 9. Static contact angle after exposure of insulation to salt fog, α = 45°

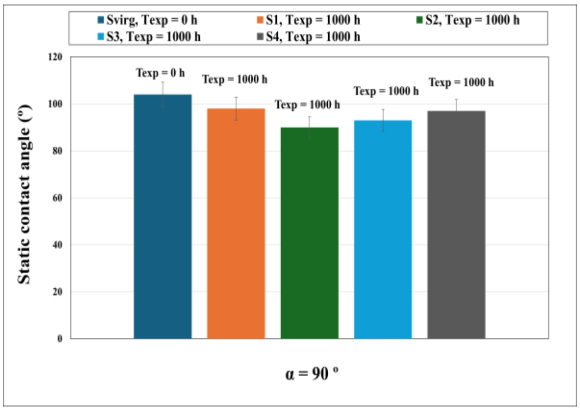


Figure 10. Static contact angle after exposure of insulation to salt fog, α = 90°

III.4 Leakage current flowing on insulating surfaces

The leakage current flowing along the surface of the samples was measured to investigate their ageing behavior as a function of exposure time to salt spray under AC voltage.

These measurements were performed on all samples; each fixed at different inclination angles α ranging from 0° to 90°. For every inclination angle, four samples (S_1, S_2, S_3, and S_4) were tested throughout the salt spray ageing period.

For each sample, highly precise measurements of the maximum leakage current (I_{max}) and minimum leakage current (I_{min}) were taken every 0.02 seconds and recorded every 15 minutes throughout the entire ageing period.

The corresponding results are presented in figures 11, 12, 13, and 14.

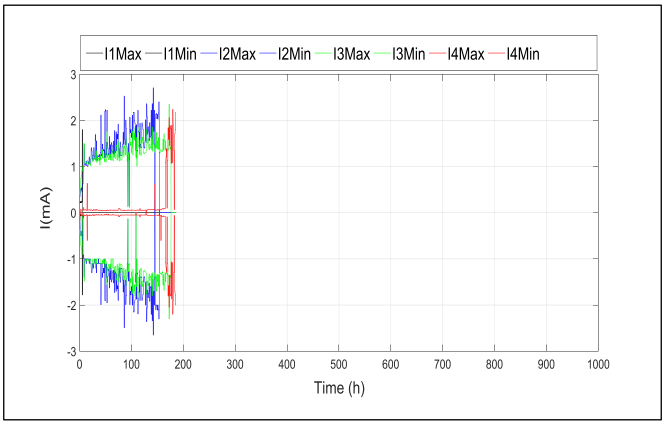


Figure 11. Leakage current flowing on S_1, S_2, S_3, S_4, α = 0° for 190 h

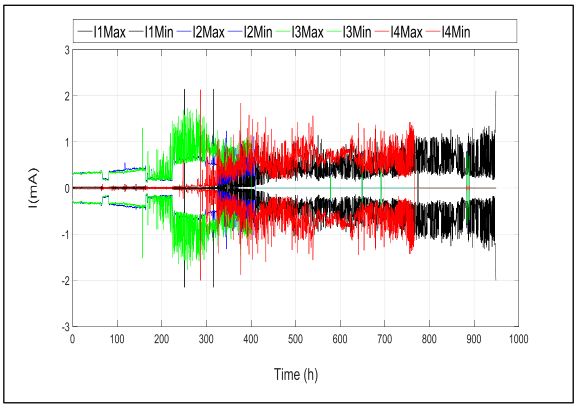


Figure 12. Leakage current flowing on S_1, S_2, S_3, S_4, $\alpha = 30°$ for 963 h

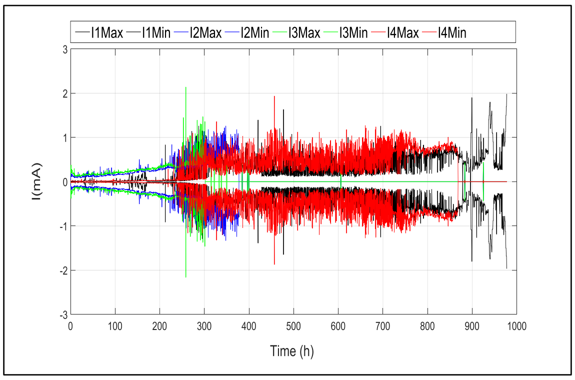


Figure 13. Leakage current flowing on S_1, S_2, S_3, S_4, $\alpha = 45°$ for 987 h

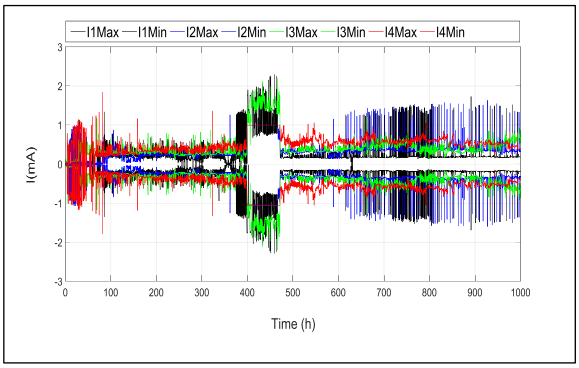


Figure 14. Leakage current flowing on S_1, S_2, S_3, S_4, $\alpha=90°$ for 1000 h

The results indicate that all samples exhibit a progressive increase in leakage current with increasing exposure time to the salt spray environment under AC voltage. Once the leakage current reaches the threshold value of 2 mA sustained for 2 seconds, the sample is considered to have failed and is consequently withdrawn from service. The time required to reach this critical value varies depending on the inclination angle of the sample. For the horizontally positioned sample, failure occurs after only 192 hours of exposure. This duration increases to 963 and 987 hours for inclination angles between 30° and 45° and exceeds 1000 hours for samples inclined at 90°.

The leakage current curves illustrated in figures 11, 12, 13, and 14 can be divided into three distinct regions [20]. The first region, referred to as the *early ageing period*, corresponds to the initial phase of testing. It is characterized by a slow and gradual increase in leakage current, indicating progressive sample degradation while maintaining surface hydrophobicity. During this phase, the leakage current waveform usually shows periodic discharge patterns. As the exposure time to the salt spray environment increases, the leakage current may reach a stable value, suggesting a temporary stabilization of the degradation process.

The second region is marked by a significant rise in leakage current, indicating the onset of hydrophobicity loss and advanced material degradation. This leads to the coalescence of water droplets on the sample surface. At this stage, the leakage current waveform displays increasingly frequent peaks and impulse discharges. This region represents the *transitional ageing period*.
In the third region, known as the *late ageing period*, the leakage current becomes substantially higher and increases rapidly until it reaches or exceeds the predefined threshold level. Water droplets adhere more strongly to the sample surface due to severe degradation and complete loss of hydrophobicity, forming a continuous conductive path between electrodes. This results in the formation of a thin moisture layer on the surface. Under the influence of Joule heating caused by the leakage current, this moisture layer evaporates, leading to the formation of dry bands and continuous surface discharges. These phenomena can ultimately result in complete sample failure [21].

It should be noted that the duration of the initial ageing period differs from one sample (S_1, S_2, S_3, S_4) to another for the same inclination and from one insulation to another depending on its inclination angle α (0°, 30°, 45°, 90°).
The longest initial ageing period, around 340 hrs was recorded when the insulation was in a vertical position. However, the shortest one (4 hrs) was recorded when the insulation was in a horizontal position.
The initial ageing period duration of polymeric insulators under salt fog conditions is a key indicator of their erosion resistance and ability to maintain electrical performance.

An extended duration of the initial ageing period observed in leakage current curves indicates superior insulation quality and enhanced resistance to erosion.

Samples positioned vertically (α = 90°) show the longest duration of this phase, reflecting greater ageing

resistance and reliability. As the inclination angle decreases, this duration shortens, suggesting decreased performance and increased susceptibility to environmental stress.

IV. Conclusion

The investigation of the impact of a silicone insulation tilt angle on its performance when subjected to combined ageing under salt fog and alternating voltage led to the following key points:

- A decrease in the hydrophobicity of silicone insulation was observed as a function of its inclination angle with respect to the horizontal and its exposure duration to the salt fog environment.
- The results of surface roughness measurements performed on the samples before and after ageing indicate a slight increase in roughness across all surfaces, which increases as its angle of inclination α increases.
- A progressive increase in leakage current was recorded for all samples as exposure time to the salt fog increased, eventually reaching a threshold value that led to their deactivation.
- The time required to reach the leakage current threshold varies from one sample to another, depending on its inclination angle with respect to the horizontal.
- The development of leakage current occurs in three distinct periods: the early aging period, the transition period, and the late aging period.
- A leakage current curve characterized by an extended early ageing period indicates good insulation quality. However, a short early ageing period suggests poor insulation quality and low resistance to erosion.

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